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Criteria for Development of a Conceptual Site Model of the Dewey-Burdock Project

Prepared in support of the Underground Injection Control Class III Area Permit for the Dewey Burdock Uranium In-Situ Recovery Project, Custer and Fall River Counties, South Dakota

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Table of Contents

Table of Figures & Tables

Acronyms

ACL – Alternate concentration limit

CSM - Conceptual site model

ISR – In-situ recovery

MCL – Maximum contaminant level

NRC – Nuclear Regulatory Commission

QA – Quality assurance

UIC – Underground Injection Control

USDW – Underground source of drinking water

USGS – United States Geological Survey

1. Introduction and General Considerations

This document provides criteria to guide the development of a conceptual site model (CSM) to support evaluation of the Dewey-Burdock Project Underground Injection Control (UIC) Class III permit application. The goal of this document is to provide criteria for developing a CSM that represents the site-specific geological, hydrogeological, and geochemical system and serves as a basis for developing a reactive transport model of the Dewey-Burdock *in-situ* recovery (ISR) site. This criteria document is accompanied by the *Conceptual Site Model Criteria Support Document for the Dewey-Burdock Project* (CSM support document), which provides additional information on the topics covered in the criteria.

The geologic setting, hydrogeologic properties, and geochemical characteristics and processes in the CSM will guide the development of inputs to the reactive transport model to predict fluid movement throughout mining and restoration operations at the site. The CSM will be based on data collected during prior characterization activities (i.e., as documented in the Class III permit application) as well as additional data collected to fill data gaps to accurately represent the Dewey-Burdock site and the anticipated processes that will affect uranium mobility.

The CSM will be iterative and will be refined as data are collected during the various, sometimes consecutive or concurrent, ISR/restoration cycles and the post-restoration stage. New data will also allow verification of modeled predictions of site behavior and support modification of the reactive transport modeling. This iterative process will also support identifying and filling data gaps over time.

The key elements for the CSM include:

- The geologic setting of the project site, including stratigraphy, lithologies, and structural and other relevant geologic features to inform an evaluation of the geologic environment in which the ISR project will occur (see Section 1);
- The hydrogeologic properties of the site, including properties of the aquifer and confining zone, groundwater flow direction, and flow rate (see Section 2); and
- The subsurface geochemistry, including the geochemistry of the groundwater and aquifer solids and the processes affecting the fate and transport of uranium (see Section 3).

The site-specific components of the CSM should describe the Inyan Kara Group (i.e., the ore-bearing injection formation); the upper confining zone (the Graneros Group); and the lower confining zone (the Morrison Formation). For completeness, any underground sources of drinking water (USDWs) outside of the injection interval (e.g., the Unkpapa Sandstone) should also be described.

Data should be collected from within the proposed extraction area (i.e., the area of the well field where the injection and production of lixiviant (fluid for ore leaching) occurs), upgradient of the proposed extraction area, and downgradient, including a margin beyond the boundary of the aquifer exemption area. The CSM should incorporate the characteristics of the field before, during, and after conducting ISR operations.

Collecting enough data to represent an entire site improves a model's ability to predict the behavior of geologic systems; the goal of this criteria document is to provide guidance on the types, amount, and spatial/temporal distribution of data that will support the development of a realistic CSM that supports the reactive transport modeling effort. This will reduce uncertainty and account for heterogeneity in site properties (e.g., permeability, mineralogy).

It may also be necessary to allow for the development of more than one CSM to accommodate uncertainty in site-specific information. For example, if data are ambiguous, sparse, or could be interpreted in more than one way, it may be appropriate to present alternatives for aspects of the CSM. Ambiguities and uncertainties in the data and CSM may be ultimately resolved with additional data collection.

The information in the CSM should be described in narrative and supported with graphics that can include maps, cross sections, tables, and other illustrations of site characteristics. The relationships among site characteristics and the relevant geologic, hydrogeologic, and geochemical processes during the course of the ISR project can be portrayed in graphics such as block diagrams, cross sectional diagrams, or flow charts. At least one comprehensive diagram should be provided showing the general site structure and stratigraphy, groundwater flow (including during ISR and restoration processes), oxidation reduction (redox) conditions, forms of uranium, and major geochemical processes (water-rock interactions). Examples of CSMs and associated graphics are provided in Appendix A.

2. Site Geology

Sufficient, detailed understanding of site geology and stratigraphy, including the depths and lithologies of the injection formation and the upper and lower confining zones, is important 1) for understanding how injected fluids will move within the formations, and 2) for ensuring that sufficient data are collected to allow simulation and prediction of fluid movement as accurately as possible.

The Inyan Kara Group includes the Lakota Formation (which includes the Chilson Member and the Fuson Shale) and the Fall River Formation (Powertech, 2013). The CSM should include all of these. Note that Fuson Shale within the Inyan Kara Group is considered to provide impedance to vertical flow between the Chilson Member and the Fall River Formation, although it does also contain channel sands. Appendix C identifies the types of geologic data about the Inyan Kara Group that will support the CSM.

Upper confinement at the Dewey-Burdock site is provided by the Graneros Group (which includes the Skull Creek Shale, Muddy/Newcastle Sandstone, Mowry Shale, and Belle Fourche Shale). The lower confining unit is the Morrison Formation (Powertech, 2013).[1]

The CSM will need to adequately describe these formations as well as general aspects of site geology. Much of this information will be based on literature about the site. Descriptions should include:

- Dip and regional structures;
- Overall site stratigraphy, including formations above and below the injection and confining zones; and

[1] An associated UIC Class V area permit is being issued for deep injection wells that will be used to dispose of treated ISR process waste fluids into the Minnelusa Formation; the Minnelusa Formation underlies the confining Morrison Formation and will not be affected by Class III injection operations and is therefore not represented in the CSM.

- Faults, fractures, or lithologic variability (e.g., higher permeability lenses) that may serve as preferential flow pathways or otherwise influence groundwater flow.

Core data supporting site characterization should include a representative number of samples to identify facies changes or heterogeneity in the formations. The cores should have few cracked or broken samples. They should be spaced laterally throughout the well field and represent samples taken at depths throughout the vertical extent of each formation in the Inyan Kara Group and the upper and lower confining zones. Cores should be subjected to appropriate analytical techniques such as tests for horizontal and vertical permeability, porosity, and mineralogic analyses or other testing to be decided upon at a later date depending on data needs. Similarly, well logs should be included from a sufficient number of wells to afford a similar level of interpretation.

2.1. Characterization of the Inyan Kara Group

Minimum data needs to characterize the Inyan Kara Group in the project area and support the CSM include the following types of information:

- Continuity of each member of the Inyan Kara Group – this may be based in part on core data or well logs at locations throughout the Dewey-Burdock project area as well as other sources of geologic information. Lateral continuity should be depicted on graphics such as geologic maps, cross sections, and block diagrams. This should consider the presence of discontinuous, localized confining units between the Upper, Middle and Lower Chilson; these units isolate the Lower/Middle Chilson injection interval from the Upper Chilson and provide a vertical permeability barrier to direct the flow of lixiviant through the extraction area. Similarly, the data should capture the presence of any localized confining units between the Upper and Lower Fall River Formation.
- Locations of the ore bodies within the Inyan Kara Group and in relation to the proposed well fields – this should be based on core data, well logs, or other information and will be depicted on graphics such as maps, cross sections, and block diagrams.
- Depths to each formation within the Inyan Kara Group – this should be based on core data or well logs at locations throughout the Dewey-Burdock project area and depicted on geologic maps, cross sections, and block diagrams.
- Top and base structure of each formation within the Inyan Kara Group – depth information should be based on core data and well logs. Structural contour maps should show the altitude of the top and base of each formation relative to a specified datum (e.g. NAVD 88).
- Thicknesses and any variations in thickness -- this should be based on core data or well logs at locations throughout the Dewey-Burdock project area and be depicted on graphics such as isopach and isochore maps, cross sections, and block diagrams.
- Information on hydraulic connections among sandstones – this should be supported by the results of aquifer tests or other data (e.g., lithology, porosity/permeability) about the formations. If more than one interpretation of the subsurface stratigraphy and hydraulic connections is possible, the different interpretations should be described in the CSM graphically and in narrative.

- Lithology and depositional history related to the potential for preferential flowpaths (e.g., high permeability channels in fluvial sediments) – this should be based on core data and literature about the site and should be depicted in the CSM graphically and in narrative.
- Petrologic and mineralogic characteristics that can affect geochemical and hydraulic properties of the units (e.g., grain size, cementation, overgrowths, nodules) – this may be available from core data and should be described in narrative and, if appropriate, noted on block diagrams.
- The CSM should also indicate areas where the mineralogical characteristics of the aquifer solids are reduced vs. oxidized (see also Section 3.2 below).

2.2. Characterization of the Confining Zones

Minimum data needs for the CSM to characterize the upper and lower confining zones within the proposed well fields include the following information types:

- Areal extent/continuity to demonstrate confinement throughout the project area – this may be based on core data or well logs at locations throughout the Dewey-Burdock project area as well as any other sources of geologic information and should be depicted on geologic maps, cross sections, and block diagrams.
- Depths to each confining zone formation – this should be based on core data or well logs at locations throughout the Dewey-Burdock project area and should be depicted on geologic maps, cross sections, and block diagrams.
- Top and base structure of each confining zone formation – depth information should be based on core data and well logs. Structural contour maps should show the altitude of the top and base of each formation relative to a specified datum (e.g. NAVD 88).
- Thicknesses and any variations in thickness – this may be based on core data or well logs at locations throughout the Dewey-Burdock project area and can be depicted on isopach and isochore maps, cross sections, and block diagrams.
- Lithology and depositional history as related to the confining properties of the formations – this may be based on core data and literature about the site.
- Petrologic characteristics that can affect geochemical and hydraulic properties of the units (e.g., cementation, overgrowths, nodules) – this may be available from core data and should be described in narrative and, if appropriate, noted on block diagrams.

3. Site Hydrogeology

Site-specific hydrogeologic information about the Inyan Kara Group informing development of the CSM should include data collected from within the proposed extraction area, upgradient of the proposed extraction area, and downgradient, including a margin beyond the boundary of the aquifer exemption area. The extent of the downgradient area/margin should be based on calculated or modeled travel times using site-specific data (e.g., injection/extraction rates, hydraulic conductivity, porosity, permeability, etc.). The map showing the locations of samples for existing groundwater data can serve as a reference when describing areas where additional data may be needed (see Figure B-1).

Sufficient, detailed understanding of site hydrogeologic parameters (porosity, permeability, storativity, and hydraulic conductivity) will support an understanding of how injected fluids will flow within the

Inyan Kara Group and be confined above and below. Pressure measurements, potentiometric data, and groundwater flow data collected as baseline data and throughout the ISR, restoration, and post-restoration phases will confirm the site is behaving as predicted. Appendix C identifies the types of hydrogeologic data about the Inyan Kara Group that will support the CSM.

For each formation within the Inyan Kara Group, the Graneros Group, and the Morrison Formation, the CSM should include several types of properties:

- Porosity – this should be based on core data and well logs; some information may be available from the literature and earlier studies of the area.
- Intrinsic permeability (horizontal and vertical) – this can be based on routine core analyses and, if available, well logging; some information may be available from the literature and earlier studies of the area.
- Hydraulic conductivity – this should be available based on pump tests or other aquifer testing data.
- Transmissivity and storativity– this should be based on pump test data or other well testing (e.g. barometric efficiency); some information may be available from the literature/earlier studies of the area.

The CSM should also address the following additional information on the Inyan Kara Group:

- Potentiometric data – this should be available from water level measurements or idle well data and be depicted on potentiometric contour maps. Baseline measurements should be collected, and the data should be updated throughout the ISR, restoration, and post-restoration phases. Data should include measurements from piezometers completed at multiple depths within the Inyan Kara Group to evaluate vertical as well as horizontal potentiometric gradients.
- Hydraulic confinement – water-level data, structural-contour maps, and formation outcrop areas will be used to determine areas where formations of the Inyan Kara Group might be unconfined.
- Pressure or hydraulic gradient – this may be based on injection/production data or water level/pressure measurements in wells. Baseline measurements should be collected, and the data should be updated throughout the ISR, restoration, and post-restoration phases.
- Groundwater flow, including directions and velocities – this may be based on tracer tests, potentiometric data, pressure data, planned ISR operations, and information in the literature. The CSM should include baseline flow, changes in flow during ISR and restoration, and establishment of post-restoration groundwater flow. The CSM should be updated based on data collected throughout the ISR project life cycle (i.e., during the ISR and restoration phases, recognizing there will be multiple ISR/restoration cycles that happen consecutively or concurrently).
- Surface recharge – this information may be available in the literature.
- Wells/artificial penetrations that extend into the Inyan Kara Group – information about these will be available in the corrective action plan as described in the UIC Class III permit application and included as a permit condition.
- Breaches in well field confining zones – if any are identified during well field pump tests, they should be investigated and documented as described in the permit.

In order to characterize any localized heterogeneity, core and well logging data supporting the hydrogeologic aspects of the CSM should include a representative number of samples spaced laterally throughout the well field and vertically within these formations. They should be analyzed by appropriate methods, with few fractured or broken samples. Pressure, potentiometric, and aquifer testing data should reflect recent testing, and subsequent testing should capture changes in groundwater levels or flow patterns due to ISR operations.

4. Geochemical Characteristics and Processes

It is crucial to characterize the geochemical properties and groundwater-solids interactions during the ISR project life cycle in order to predict the speciation and mobility of uranium and other metals in the ore body (e.g., vanadium, selenium, molybdenum, and arsenic). The geochemical aspects of the CSM should cover the pre-operational, ISR, restoration, and post-restoration phases. Information and samples need to represent the upgradient, extraction area, and downgradient regions, including the potential for off-site excursions.

During the project life cycle, the general sequence of interactions between fluids (groundwater and lixiviant) can be described as:

1. Interactions between the lixiviant and solids in the extraction area during ISR operations;
2. Interactions between the post-ISR solids and the restoration fluid;
3. Interactions between the post-ISR solids and the upgradient groundwater that moves into the restored zone after restoration has been completed;
4. Interactions between the downgradient solids and the initial slug of restored groundwater that moved downgradient; and
5. Interactions between the downgradient solids and the upgradient groundwater that has passed through the restored zone.

The CSM will be supported by existing field data in addition to any new sample results to represent baseline conditions, fill data gaps, and direct subsequent monitoring. Appendix B contains a map showing the locations of wells with groundwater quality data in the Chilson and Fall River formations; data from these wells and cores are presented in the Dewey-Burdock Project UIC Class III permit application (Powertech, 2013). This map can be used to show how new sample locations are selected to fill data gaps. Attention should be paid to changing geochemistry as ISR proceeds and as the system stabilizes after restoration. Laboratory experiments will be needed to estimate parameters related to processes controlling uranium mobility and retention.

Factors contributing to uncertainty should be described in the CSM. For example, heterogeneities in mineralogy and the resulting variability in the properties of the solids (e.g., sorption capacity) can affect the mobility of uranium and other metals. Challenges to fully representing spatial and temporal variability in groundwater and solids sampling should be explained. Uncertainties in analytical methods should also be discussed.

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4.1. Groundwater Geochemistry

To describe the general geochemical environment, the groundwater constituents should include, at a minimum, basic water quality parameters, base cations and major anions, uranium, and other constituents that can affect the speciation and mobility of uranium and other metals. These include:

- Temperature;
- pH;
- Dissolved oxygen;
- Specific conductance;
- Redox potential;
- Carbon dioxide;
- Base cations (calcium, magnesium, potassium, and sodium);
- Major anions (chloride, nitrate, sulfate);
- Total alkalinity as $CaCO_3$;
- Bicarbonate at HCO_3^-;
- Total dissolved solids; and
- Total and dissolved organic carbon.

In particular, a conservative tracer such as chloride can help monitor for fluid excursion outside of the project area (Deutsch et al., 1983). The chemistry of the lixiviant (including ion exchange effluent after uranium removal) and restoration fluid should also be represented in the CSM, including the dissolved oxygen content when injected. Samples that are collected should be filtered.

For a robust CSM, development of the geochemical model, and monitoring for potential mobilization of metals during ISR, a more complete set of analytes will be needed. Powertech (2013) provides a summary of existing groundwater quality data for the Fall River and Chilson formations (Table 17.5 in Appendix N of Powertech, 2013). [REF _Ref6908783 \h] below is a comprehensive analyte list that includes heavy metals that could be mobilized during the ISR project and should be considered for inclusion in the CSM. These include vanadium, arsenic, chromium, zinc, nickel, cerium, thorium, and copper, among others. Some, such as uranium and chromium, are redox-sensitive, so that changes in subsurface redox conditions may affect their mobility. Iron and manganese, also redox-sensitive, should be included in the CSM because of the role of iron and manganese oxides and oxyhydroxides in metals sorption (Langmuir et al., 2005).

Table [SEQ Table * ARABIC]. Baseline Water Quality Parameter List.
Source: U.S. EPA (2019)(Table 13).

Test Analyte/Parameter[1]	Units	Analytical Method
Physical Properties		
pH[2]	pH Units	A4500-H B
Total Dissolved Solids (TDS)	mg/L	A2540C
Specific Conductance[8]	µmhos/cm	A2510B or E120.1
Common Elements and Ions		
Total alkalinity (as Ca CO_3)	mg/L	A2320B
Bicarbonate Alkalinity (as Ca CO_3)	mg/L	A2320B (as HCO_3)
Calcium	mg/L	E200.7
Carbonate Alkalinity (as Ca CO_3)	mg/L	A2320B
Chloride, Cl	mg/L	A4500-Cl B, E300.0
Magnesium, Mg	mg/L	E200.7
Nitrate, NO_3^- (as Nitrogen)	mg/L	E300.0
Potassium, K	mg/L	E200.7
Silica, Si	mg/L	E200.7
Sodium, Na	mg/L	E200.7
Sulfate, SO_4	mg/L	A4500-SO_4 E, E300.0
Total Metals		
Aluminum, Al	mg/L	E200.7, E200.8, E200.9
Antimony, Sb	mg/L	E200.8, E 200.9
Arsenic, As	mg/L	E200.8
Barium, Ba	mg/L	E200.8
Beryllium Be	mg/L	E200.7, E200.8, E 200.9
Boron, B	mg/L	E200.7
Cadmium, Cd	mg/L	E200.8
Chromium, Cr	mg/L	E200.8
Copper, Cu	mg/L	E200.8
Fluoride, F	mg/L	E300.0
Iron, Fe	mg/L	E200.7
Lead, Pb	mg/L	E200.8
Manganese, Mn	mg/L	E200.8
Mercury, Hg	mg/L	E200.8
Molybdenum, Mo	mg/L	E200.8
Nickel, Ni	mg/L	E200.8
Selenium, Se	mg/L	E200.8
Silver, Ag	mg/L	E200.8, A3114 B
Strontium, Sr	mg/L	E272.1, E272.2, E 200.7
Thallium, Tl	mg/L	E200.8, E200.9
Thorium, Th	mg/L	E200.8
Uranium, U	mg/L	E200.7, E200.8
Vanadium, V	mg/L	E200.7, E200.8
Zinc, Zn	mg/L	E200.8
Radiological Parameters		
Gross Alpha	pCi/L	E900.0
Gross Beta	pCi/L	E900.0
Gross Gamma	pCi/L	E901.1

Test Analyte/Parameter[1]	Units	Analytical Method
Lead 210	pCi/L	E905.0 Mod.
Polonium 210	pCi/L	RMO-3008
Radium, Ra-226	pCi/L	E903.0
Thorium 230	pCi/L	EPA 910, ATSM D3972-90M

[1]Laboratory analysis only, except where indicated.
[2]Field and Laboratory

Separation of colloidal and dissolved uranium fractions should be performed by ultrafiltration on a subset of samples to assess the potential for colloid-facilitated transport of uranium and other metals; this can be calculated by the difference between total concentration and concentration in the filtrate. Samples should be analyzed by approved methods as specified in the permit application and monitoring plan.

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4.2. Solid Phase Geochemistry

Characterization of solid phase geochemistry in core samples should include:

- The mineralogy of the Fall River Formation and Chilson Member;
- Oxidation state and forms of uranium (e.g., mineral form as uraninite or coffinite, organic-associated, present as discrete mineral grains, present as coatings/overgrowths on existing minerals, adsorbed onto mineral surfaces);
- Background solids characteristics as well as the amounts and forms of residual uranium in post-ISR cores;
- Potential evaluation of microbial populations, especially in post-ISR cores; and
- Amount of organic matter.

Multiple locations will be needed in the ISR zone, upgradient, and downgradient. Analyses should be performed on cores from various lithologies that have been determined based on well logging and visual core examinations. The CSM will be supported by existing data from previous efforts as well as any additional sampling needed to fill data gaps so that the project area is well-represented. Differing mineralogies of the Dewey and Burdock areas should be represented. For cores expected to be anoxic, sample collection must preserve anoxic conditions.

While basic information about lithology and mineralogy is covered in Section 1, more in-depth characterization of aquifer solids is discussed here. Analyses should include a suite of methods that may include:

- Mineral and texture evaluation by transmitted light microscopy and scanning electron microscopy (SEM);
- Identification of major minerals by X-ray diffraction;
- Chemical information by SEM (energy-dispersive X-ray spectroscopy), sample digestion and analysis (e.g., by ICP-MS), and solids analyses for sulfur and organic carbon;
- Valence state of uranium – (e.g., X-ray absorption near-edge spectroscopy (XANES)); and
- Speciation of uranium, iron, and manganese by sequential extractions (exchangeable, organically bound, poorly crystalline/amorphous forms, crystalline forms).

Minerals that may be identified during routine examination of samples are listed in [REF _Ref19434602 \h].

Table [SEQ Table * ARABIC]. Common minerals found during routine sample examination Source: Saunders et al. (2016).

Rock-forming minerals: quartz, feldspars, micas
Calcite and other carbonates (e.g., dolomite, siderite)
Crystalline iron (III) minerals (hematite, magnetite)
Poorly crystalline iron and manganese oxyhydroxides and aluminum hydroxide (gibbsite)
Native arsenic and selenium
Uranium-bearing minerals (uraninite/pitchblende, coffinite)
Kaolinite, clays (smectite, chlorite)
Sulfides (primarily pyrite)
Other transition metal-bearing minerals (e.g., V: haggite, doloresite; Mo: jordisite)
Sulfates

There are several possible forms of refractory uranium in the post-ISR extraction areas that can be represented in the CSM (Gallegos et al., 2015):

- Uranium (IV) associated with refractory organic carbon, likely as grains of uraninite or coffinite – this uranium would remain immobile if conditions remain reducing.
- Uranium (VI) associated with alteration products of pyrite or chlorite, including Fe oxyhydroxides – this pool of uranium may be more mobile depending on evolving groundwater conditions.
- Secondary Uranium(VI) minerals – this may occur as new uranium-rich mineral coatings; their mobility will depend on evolving groundwater conditions.

Although identification and quantification of the forms and oxidation states of uranium is a primary focus, attention should be paid to other metals for which there are drinking water standards or alternate concentration limits (ACLs) and that may be affected by geochemical and biogeochemical processes at the project site.

Characterization of microbial communities may be considered in order to evaluate the potential for microbial processes to 1) affect uranium recovery by directly or indirectly mediating the oxidative solubilization of uranium; or 2) establish reducing conditions after restoration through the microbially mediated reduction of uranium (VI) and other redox-sensitive metals such as iron (III) coupled to the degradation of organic matter (Zammit et al., 2014; Lovley and Phillips, 1986).

The CSM should reflect the results of the solids characterization by indicating parts of the project area where the solids are reducing vs. oxidizing, paying particular attention to the redox characteristics of the areas downgradient of the ISR zone. This can be represented on a map similar to Figure 3 from Johnson and Tutu (2016).

4.3. Geochemical Processes

4.3.1. ISR Phase Reaction of the Lixiviant with the Solids in the Extraction Area

The lixiviant at the proposed site will use oxygen and carbonate to oxidatively dissolve U(IV) and promote mobility through complexation. The CSM should represent:

- Oxidation of uranium (IV) minerals (uraninite, pitchblende, coffinite) to form uranium (VI);
- Aqueous complexation of U(VI) to form mobile carbonate and ternary Ca-carbonate-U complexes. The predominant species in groundwater are expected to be $UO_2CO_3^0$, $(UO_2)CO_3(OH)^{3-}$, $Ca_2UO_2(CO_3)_3^0$, and $CaUO_2(CO_3)_3^{2-}$;
- Oxidation of pyrite, chloride, or other Fe(II) and Mn(II)-bearing minerals to form Fe(III) and Fe(IV) oxyhydroxides;
- Oxidation of Fe^{2+} and Mn^{2+} in anoxic groundwater to form Fe(III) and Mn(IV) oxyhydroxides.
- Potential adsorption of uranium onto Fe(III) and Mn (IV) oxyhydroxides, mixed Fe(II)/ Fe(III) phases, or clays; and
- Lixiviant pumping and ion exchange treatment to remove uranium and subsequent reinjection.

4.3.2. Restoration Stage

Two options for the restoration process are described in the permit application:

- Reverse osmosis (RO) of wastewater with injection of the permeate as restoration fluid; and
- Disposal of wastewater by land application and use of groundwater from the Madison Limestone for a clean groundwater sweep.

Because the RO permeate will have lower ion concentrations than groundwater from the Madison Limestone, the interactions between the restoration water and the leached ore solids are expected to differ for the two restoration process choices (Powertech, 2013). If a restoration process has not been selected when the CSM is developed, then the potential use of both methods should be represented, and the chemistries of both types of restoration fluid will be needed for the geochemical modeling. The anticipated dissolved oxygen concentrations of the restoration fluids should be identified because higher dissolved oxygen favors uranium mobility.

4.3.3. Post-Restoration Stage

The CSM should reflect the geochemical processes and factors that may govern uranium mobility both in the leached zone and downgradient. Other heavy metals that should be considered for inclusion in the CSM (and for possible monitoring) include vanadium, arsenic, molybdenum, selenium, chromium, zinc, nickel, cerium, thorium, and copper. Some, such as uranium and chromium are redox-sensitive, and redox conditions in the subsurface will affect their mobility. Iron and manganese and their geochemical speciation under oxidized and reduced conditions should be included in the CSM because of the role of iron and manganese oxides and oxyhydroxides as substrates for metals sorption (Langmuir et al., 2005).

Some factors affecting the amount and speciation of uranium persisting in the ISR zone that may be included in the CSM include (Gallegos et al., 2015):

- The potential for localized heterogeneity in redox conditions due to variability in organic matter content in the solids;
- Possible regions of groundwater bypass due to lithologic variability, leading to variability in contact between the solids and the lixiviant; and
- Variability in original uranium content and iron and manganese-bearing minerals in the solids.

Note that the CSM should reflect differences in the solid phase geochemistry between the Dewey and Burdock areas, particularly with respect to calcite, pyrite, organic matter, and the form of uranium (e.g., separate-phase minerals vs. adsorbed or organically bound) in these two areas (Johnson et al., 2013).

4.3.4. Processes and Factors Controlling Uranium Mobility

Sorption is a key process expected to affect the mobility of uranium and other metals at Dewey-Burdock during ISR, in the restored ISR zone, and in oxidized aquifer solids in the downgradient areas (Johnson et al., 2016; Johnson and Tutu, 2016; Johnson and Tutu, 2013). Also, uranium reduction and precipitation would retard uranium mobility under reducing conditions. The geochemical processes involved in uranium fate and transport are complex and dynamic, and this should be acknowledged in the CSM.

Several types of geochemical processes should be evaluated for inclusion in the CSM:

- The potential for sorption of uranium (as uranyl ion; UO_2^{2+}) and other heavy metals onto primary or secondary iron and manganese oxides and oxyhydroxides or clay minerals in oxidized solids. This process can be represented where the mineralogy contains these minerals and should acknowledge the sensitivity of sorption to fluid pH.
- Possible spreading of the zone of sorbed uranium and other heavy metals over time through ongoing adsorption/desorption and dispersion of uranium in the groundwater. This can be indicated in the CSM as a potential process in the oxidized zone where sorption substrates such as iron and manganese oxides and oxyhydroxides, aluminum oxides, and organic matter in the solids are available to control sorption.
- The role of competition for sorption sites from other cations in controlling the retardation of uranium and other metals. This can be indicated in the CSM as a potential process in the oxidized zone where sorption substrates such as iron and manganese oxides and oxyhydroxides, aluminum oxides, and organic matter in the solids are available to control sorption.
- The potential for colloid-facilitated transport via sorption of uranium and other heavy metals onto colloid-size particles should be evaluated and included in the CSM if appropriate. Colloid facilitated transport can be included as a possible vehicle for migration of uranium and other metals in groundwater.

- Whether there is the potential for the establishment of reducing conditions in the ISR zone post-restoration. This can be included in the CSM if dissolved oxygen is expected to be low and depending on the organic carbon content; note that reducing conditions may be established locally.
- The immobilization of uranium by reduction of U(VI) to U(IV) and formation of low solubility uranium minerals (uraninite, pitchblende, and coffinite) in areas where there are
- The possibility of reductive dissolution of U(IV)-bearing minerals and mobilization of uranium post-restoration. This process may occur during restoration if there were localized areas in the extraction area that were hydraulically bypassed during ISR.

Geochemical characteristics of the groundwater and solids could lead to return of more elevated of uranium concentrations in the extraction area at Dewey-Burdock. The following are examples of factors that should be evaluated for representation in the CSM:

- Calcite content in the solids - The presence of calcite decreasing the adsorption of uranium onto aquifer solids through increased formation of mobile calcium-uranyl -carbonate complexes due to carbonate in the water.
- pH - The effects of pH changes on uranium mobility due to changes in aqueous speciation.
  - The potential for increased calcium-uranyl-carbonate complexation in groundwater at higher pH; possible mobilization of adsorbed uranium if upgradient groundwater with higher pH migrates into the restored zone.
  - The potential for calcite precipitation at higher pH, leading to reduced carbonate in solution and less formation of mobile uranium-carbonate complexes.
- Calcium concentrations - Effects of changes in groundwater calcium concentration on formation of calcium-uranyl-carbonate complexes.

4.3.5. Laboratory Experiments

Laboratory experimentation will be needed to obtain data on:

- The sorption of uranium onto mineral phases at Dewey-Burdock (batch sorption experiments);
- The reaction kinetics of uranium sorption onto mineral solids (column experiments);
- The potential for leaching of persistent uranium by restoration fluids and upgradient; and groundwater migrating into the restoration zone (batch and column leaching studies).

The following criteria should be used in planning laboratory experiments:

- For all experiments, adequate samples should be chosen to represent heterogeneity in the solids. This includes mineralogy, especially the quantity and forms of solid-phase iron and manganese, organic carbon, and the presence and amount of calcite. Aquifer solids should have been characterized as per Section 3.2 above. If the solids are reduced, sample handling must maintain anoxic conditions.
- The chemistry of the matrix waters should represent, to the degree feasible, the major ion chemistry of the restoration water, upgradient groundwater, and evolved upgradient groundwater after it has passed through the restored zone.
- Batch sorption and column tests should include interactions of solids in the restored zone with upgradient groundwater and interactions of downgradient solids with restoration water,

upgradient groundwater, and evolved upgradient groundwater after it has passed through the restored zone.

- The pH, CO_2, alkalinity, and dissolved oxygen of the fluid should be chosen to represent either documented or likely pre-ISR, active ISR, restoration, and post-restoration site conditions. Existing data (Powertech,2013) for the Fall River and Chilson show the ranges provided in [REF _Ref19429017 \h * MERGEFORMAT].

Table [SEQ Table * ARABIC]. Analyte detected ranges in Fall River Formation and Chilson Member. Source: Powertech (2013)

		Fall River		Chilson	
Analyte	**Units**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Field Dissolved Oxygen	mg/L	0.07	5.42	0.14	3.29
Field pH	s.u.	6.73	8.44	6.92	8.31
Alkalinity, Total as $CaCO_3$	mg/L	117	197	71	261
Calcium, Dissolved	mg/L	30	368	35	386
Uranium, Suspended	mg/L	<0.0003	0.0031	<0.0003	0.0014
Uranium, Total	mg/L	<0.0003	0.11	<0.0003	0.02
Uranium 238, Dissolved	pCi/L	<20	<20	<20	<20
Total Dissolved Solids (Calculated)	mg/L	826	2,178	733	2,348

- Batch sorption experiments should be run long enough to allow samples to achieve equilibrium.
- For column experiments, flow rates should be set to represent the range of flow rates representative of the site plus or minus error. The rationale for the duration and number of pore volumes run should be clearly explained. A conservative tracer should be initially run.
- Column experiments should include tests in which flow is temporarily halted to observe rebound effects.
- Batch and column sorption experiments should be conducted using a range of uranium concentrations consistent with the original groundwater concentrations and potential increased uranium concentrations due to ISR. The uranium concentrations should include the approximate full range of values representative of the site to provide multiple calibration points for geochemical modeling.
- Analysis of fluids from all samples should be conducted using U.S. EPA-approved methods consistent with those used for groundwater analyses.
- In addition to laboratory experiments, field-scale studies should be conducted where feasible to provide the most representative information concerning the mobility of uranium and other metals (see Johnson and Tutu, 2016).

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5. Considerations for Ensuring Quality Data

Data need to be of adequate quality to meet the needs of this project. It is understood that Quality Assurance Project Plans associated with any data collection will be followed. Below are several additional considerations for ensuring and documenting data quality:

- All groundwater samples should be analyzed using methods approved by U.S. EPA and documented with the appropriate quality assurance (QA) samples (blanks and duplicates). Charge balance on water quality samples should be calculated as another measure of data quality.
- Core sample analyses and well logs should be analyzed by knowledgeable analysts, and the resulting data should be supported by a detailed report that includes: well log analyses (including well logs); core analyses; and a descriptive report interpreting the results.
- Solids characterization (e.g., microscopy, XANES, XRD) should be conducted according to accepted best practices, and data and QA measures (e.g., use of internal standards) should be noted.
- Groundwater or solids samples collected from low-oxygen settings must be maintained under low-oxygen conditions. Documentation should be maintained regarding handling for all samples with respect to protection from atmospheric exposure, if appropriate, or for preservation of any unstable constituents.
- Laboratory experiments should be conducted at least in duplicate for each set of experimental conditions.
- The representativeness of groundwater and core samples should be demonstrated using maps to show coverage of all project areas (collectively with both existing and new data).
- Because data will come from multiple sources, including previous studies as well as new data, inconsistencies in information should be noted and evaluated. If there are deficiencies in procedures for older/existing data or there is insufficient information to assess data quality, well-documented newer data for a given area (and depth) should take precedence.
- Uncertainties and limitations in data should be clearly stated for all analyses and the consequences for site geochemistry should be noted in development of the CSM.

5.

6. References

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Appendix A: Conceptual Site Model Guides and Examples

The formats and presentations of information can vary greatly among CSMs depending on project needs. The following reports and articles may serve as useful reference documents and examples of CSMs for various project types.

Dam, W.L., Campbell, S., Johnson, R.H., Looney, B.B., Denham, M.E., Eddy-Dilek, C.A., and Babits, S.J. 2015. Refining the site conceptual model at a former uranium mill site in Riverton, Wyoming, USA. Environ. Earth Sci. published online July 7, 2015. DOI 10.1007/s12665-015-4706-y

Johnson, R. H, and Tutu, J. 2016. Predictive Reactive Transport Modeling at a Proposed Uranium *In-Situ* Recovery Site with a General Data Collection Guide. Mine Water Environment, 35: 369-380.

Logan, M., Gillow, J., and Murphy, R., 2015. Geochemical Conceptual Site Models Validated by Speciation Data to Support In Situ Treatment Strategies for Metals. [HYPERLINK "https://www.esaa.org/wp-content/uploads/2015/06/08-Logan.pdf"]. Accessed 5/31/2019.

Neptune and Company, 2014. Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility. NAC-0018_R4. [HYPERLINK "https://deq.utah.gov/legacy/businesses/e/energysolutions/depleted-uranium/performance-assessment/compliance-report/docs/2014/07Jul/supinfo/appreferences/CliveDU%20ACSM.pdf"]. Accessed 5/31/2019.

New Jersey Department of Environmental Protection. 2011. Site Remediation Program: Technical Guidance for Preparation and Submission of a Conceptual Site Model. Version 1.0. [HYPERLINK "https://www.nj.gov/dep/srp/guidance/srra/csm_tech_guidance.pdf"]. Accessed 5/31/2019.

Nikolaidis and Shen, 2000. Conceptual Site Model for Evaluating Contaminant Mobility and Pump-and-Treat Remediation. Global Nest: the Int. J. Vol 2, No 1, pp 67-76. [HYPERLINK "https://journal.gnest.org/sites/default/files/Journal%20Papers/Nikolaidis.pdf.%20Accessed%20 5/31/2019"]. (Note: Figure 1 in the paper is a flow chart showing the process for developing a CSM).

Example Graphics

Below are examples of CSM graphics showing the significant site features and processes. These examples are from subsurface projects and show how cross-sectional diagrams and maps can be used to illustrate site characteristics and relevant geochemical and hydrologic processes.

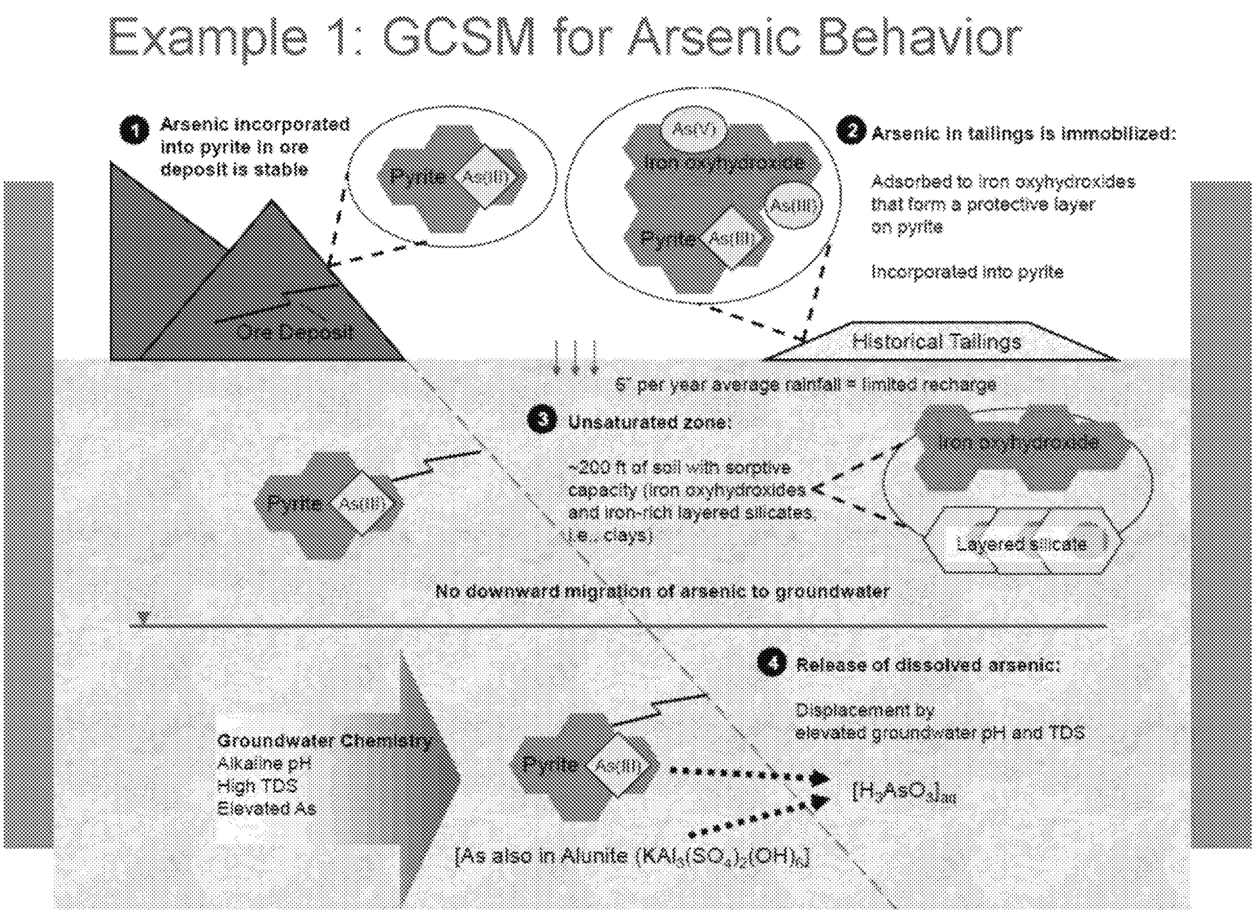

Figure A- [SEQ Figure_A- * ARABIC]. Geochemical conceptual site model for arsenic behavior in the subsurface at a historical mining site.

Source: Logan, M., Gillow, J., and Murphy, R. 2015. Geochemical Conceptual Site Models Validated by Speciation Data to Support In Situ Treatment Strategies for Metals. Arcadis. Retrieved from: [HYPERLINK "https://www.esaa.org/wp-content/uploads/2015/06/08-Logan.pdf"]. Accessed 5/31/2019.

This diagram shows a geochemical site conceptual model developed to help assess the potential for arsenic mobility at a site with historical mining. It shows the groundwater constituents, minerals, and processes that affect the speciation (chemical forms) and mobility of arsenic.

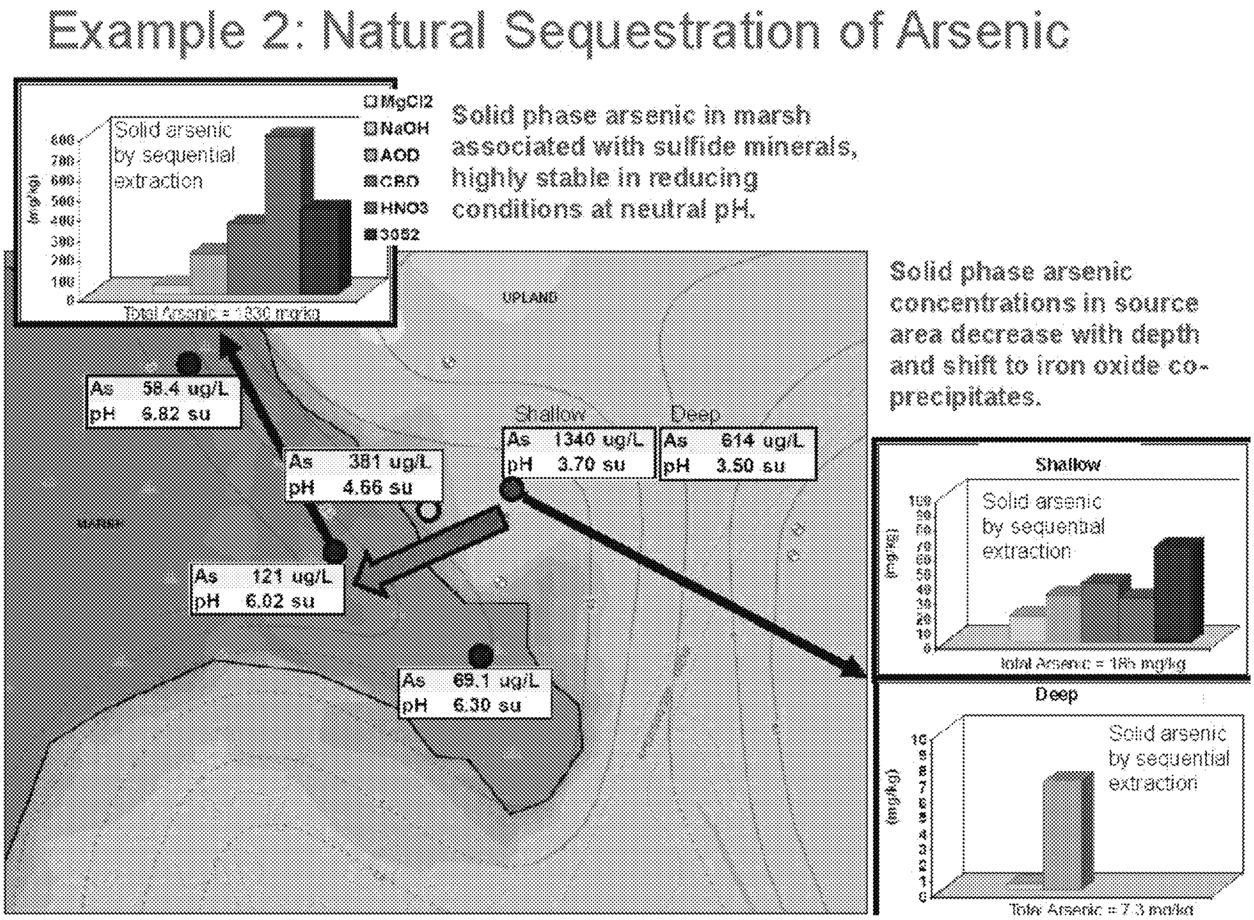

Figure A- [SEQ Figure_A- * ARABIC]. Natural sequestration of arsenic at a historical mine site, shown in map format.

Source: Logan, M., Gillow, J., and Murphy, R. 2015. Geochemical Conceptual Site Models Validated by Speciation Data to Support In Situ Treatment Strategies for Metals. Arcadis. Retrieved from: [HYPERLINK "https://www.esaa.org/wp-content/uploads/2015/06/08-Logan.pdf"]. Accessed 5/31/2019.

This figure is part of the development of a geochemical site conceptual model for a site with historical mining activities. The map shows that site characterization, including concentrations and forms of arsenic (e.g., solid phase) and groundwater flow direction.

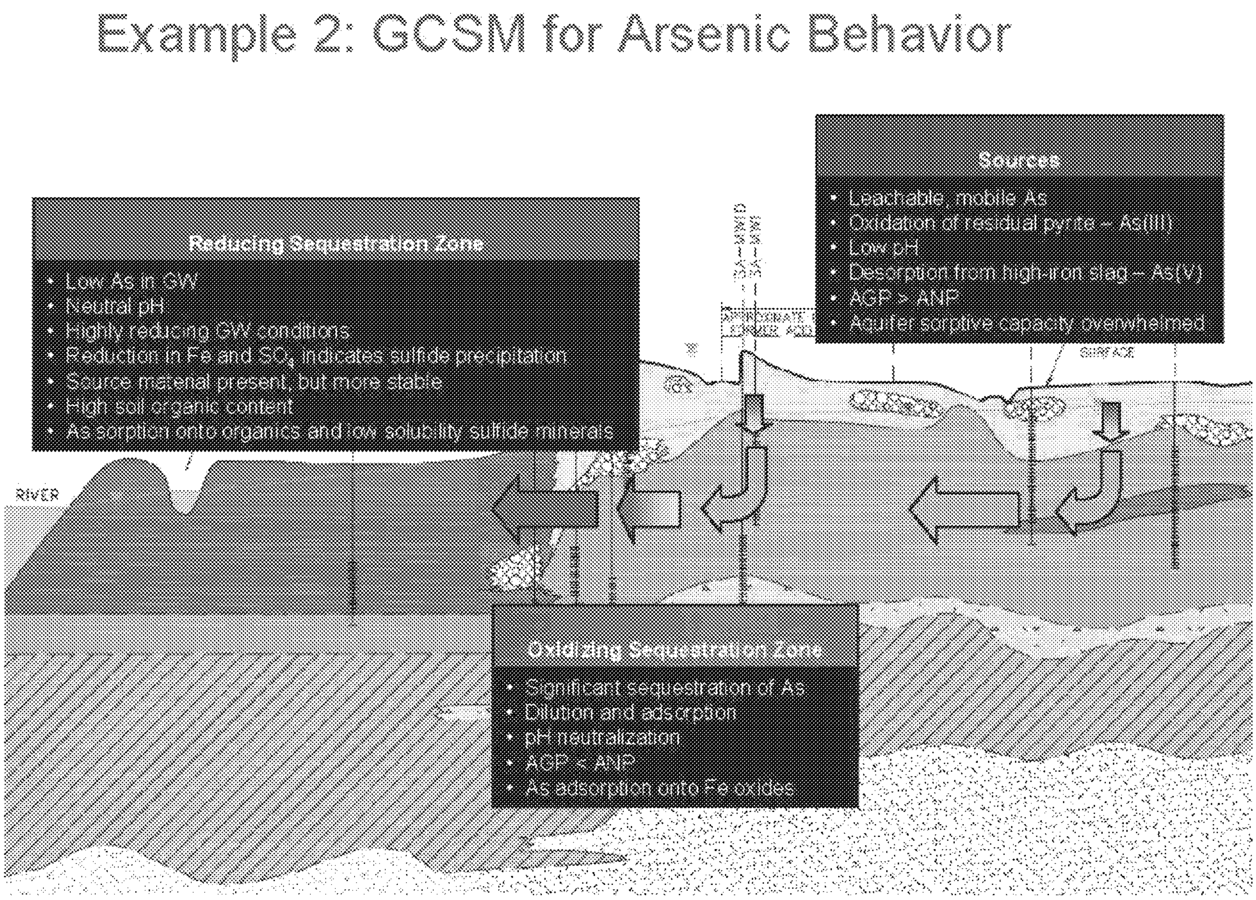

Figure A- [SEQ Figure_A- * ARABIC]. Geochemical conceptual site model for arsenic behavior showing redox zones.

Source: Logan, M., Gillow, J., and Murphy, R. 2015. Geochemical Conceptual Site Models Validated by Speciation Data to Support In Situ Treatment Strategies for Metals. Arcadis. Retrieved from: [HYPERLINK "https://www.esaa.org/wp-content/uploads/2015/06/08-Logan.pdf"]. Accessed 5/31/2019.

This figure is part of the development of a geochemical site conceptual model for a site with historical mining activities. It illustrates the oxidizing and reducing zones along with the basic geologic setting, and it shows the basic geochemical characteristics and processes.

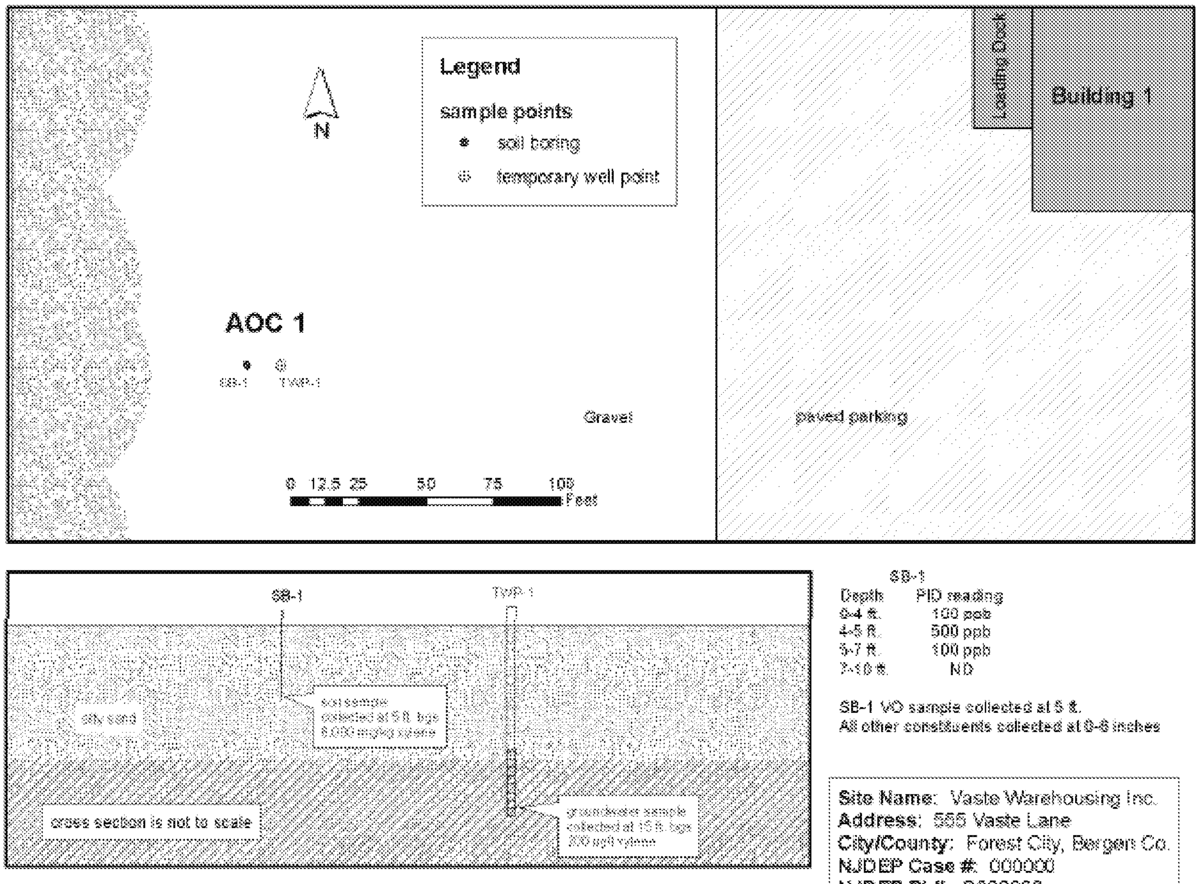

Figure C2-1: Schematic of a site showing sampling conducted and the site specific information collected for a single AOC during the Site Investigation.

Figure A- [SEQ Figure_A- * ARABIC]. Schematic of a site showing sampling conducted and the site specific information collected for a single AOC during the Site Investigation.

Source: New Jersey Department of Environmental Protection. 2011. Site Remediation Program: Technical Guidance for Preparation and Submission of a Conceptual Site Model. Version 1.0. [HYPERLINK "https://www.nj.gov/dep/srp/guidance/srra/csm_tech_guidance.pdf"]. Accessed 5/31/2019.

This diagram in a site conceptual model guidance document shows maps and a cross section to illustrate sampling at the site and other information.

Additional Graphics

Zammit, C., Brugger, J., Southam, G., and Reith, R., 2014. *In-situ* recovery of uranium — the microbial influence. Hydrometallurgy 150, 236–244.

This journal article reviews the interactions between microorganisms and uranium and the potential effects on ISR operations. Figure 5 in the paper is a cross section style graphic of a conceptual model of a uranium roll-front deposit showing the relevant geochemical and biogeochemical processes.

Appendix B: Map of Sampling Locations at the Dewey-Burdock Site

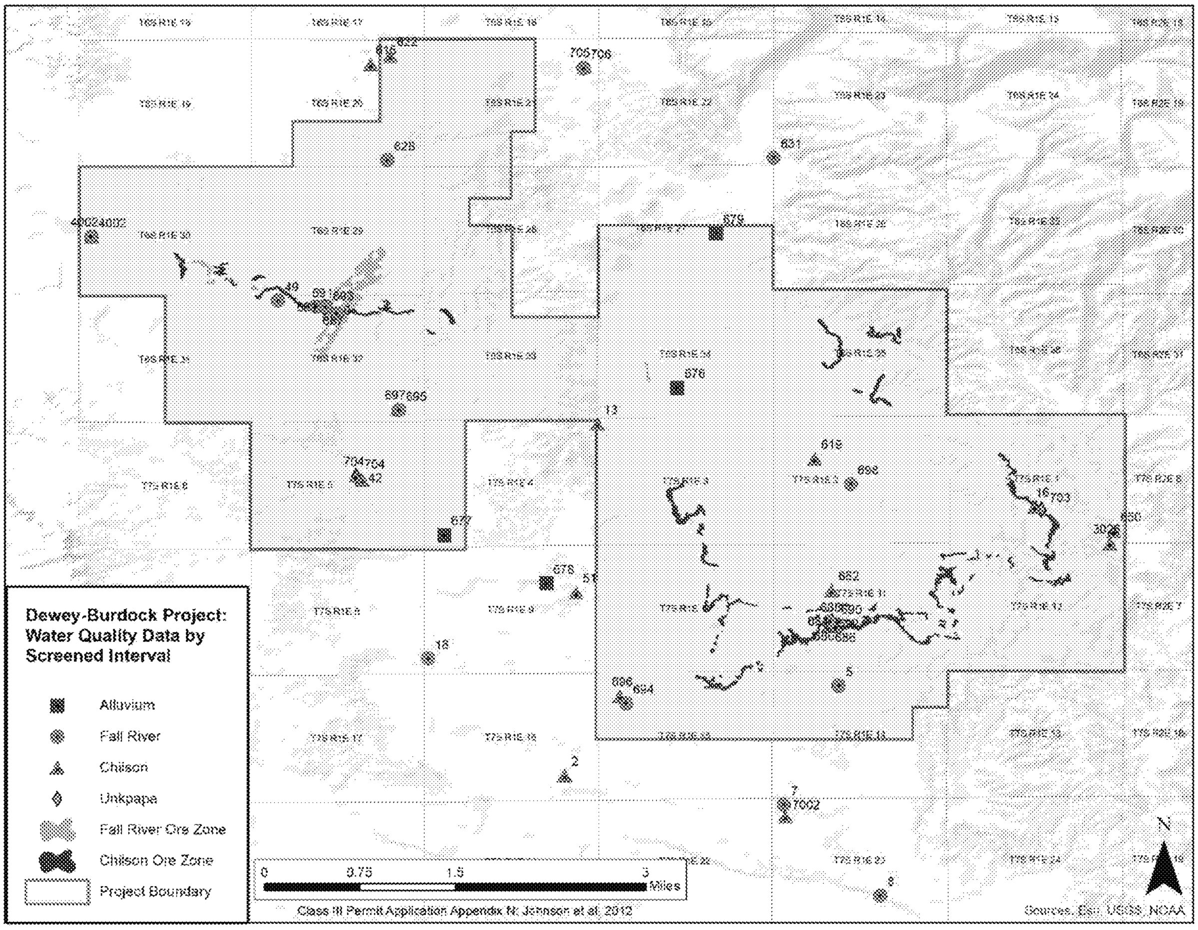

Figure B- [SEQ Figure_B- * ARABIC]. Map of Dewey-Burdock project area showing locations of wells with water quality data.
Sources: Johnson (2012) and Powertech (2013).

Sources:

Johnson, R.H. 2012. Geochemical data from groundwater at the proposed Dewey Burdock uranium in-situ recovery mine, Edgemont, South Dakota: U.S. Geological Survey, Open-File Report 2012–1070, 11 p. Retrieved from https://pubs.usgs.gov/of/2012/1070/. Accessed 9/16/2019.

Powertech Inc. 2013. Dewey-Burdock Project Class III Underground Injection Control Permit Application. [HYPERLINK "https://www.epa.gov/sites/production/files/2015-08/documents/dbapplication_1.pdf.%20Accessed%209/16/2019"].

Appendix C: Characterization of the Geologic Units

The tables below can be used to tabulate the geologic, hydrogeologic, and geochemical characteristics of the Inyan Kara Group, the Graneros Group, and the Morrison formations. Hypothetical example information is provided in some cells. These tables can be used to summarize the elements needed for the CSM, to identify data gaps, and to indicate when data gaps are filled.

Table C- [SEQ Table_C- * ARABIC]. Characterization of geologic, hydrogeologic, and geochemical characteristics of the Inyan Kara Group, the Graneros Group, and the Morrison Formation.

		Inyan Kara Group – Characterization of Data Availability		
		Lakota Formation		Fall River
Project phase:				
	Data source	Chilson Member	Fuson Shale	Fall River
Geologic Data (Section 1)				
Areal extent	Core data, well logs			
Locations of ore bodies	Core data, well logs			
Depth	Core data, well logs	*"Fairly well characterized in the well field; less complete upgradient."*		
Thickness	Core data, well logs			
Lithology/ depositional history	Core data and literature about the site			
Petrology/mineralogy	Core data			
Hydrogeologic Data (Section 2)				
Hydraulic connections among sandstones	Aquifer test results or other data			
Porosity	Core data; literature/historic studies	*"Values range from XX% to XX%, with a mean of XX%. Good coverage in areas XXX, less complete in area XXX."*		
Intrinsic permeability (V and H)	Core data; literature/historic studies			
Transmissivity and storativity	Pump tests; literature/earlier studies			

Potentiometric data	Water level measurements, idle well data. (Baseline data plus updates in the ISR, restoration, & post-restoration phases.)	*"Fairly good coverage in XXX area of the well field. Limited data in area XXX. Data are from the years XXXX and XXXX."*		
Pressure or hydraulic gradient	Injection/production data or water level/pressure measurements in wells. (Baseline data plus updates in the ISR, restoration, & post-restoration phases.)			
Groundwater flow direction/velocity	Tracer tests; literature. (Baseline data plus updates in the ISR, restoration, & post-restoration phases.)			
Hydraulic conductivity	Pump test data			
Surface recharge	Described in the literature			
Wells/artificial penetrations	UIC permit application			
Geochemical Data (Section 3)				
Basic water quality parameters (e.g. pH, TDS, temperature, dissolved oxygen, etc.)	Well sampling			
Groundwater constituents affecting uranium speciation and mobility (e.g. total U, Ca, Mg, CO_2, alkalinity, total and dissolved organic carbon, etc.)	Well sampling			
Trace and minor elements in	Well sampling			

groundwater (e.g. iron, heavy metals)				
Oxidation states and forms of uranium in solids (e.g. uraninite, coffinite, residual U in solids, etc.)	Core data; petrographic and mineralogic analyses			
Reactive and non-reactive minerals such as hematite and magnetite, carbonates, clays, sulfides, sulfates, etc.	Core data; petrographic and mineralogic analyses			

		Graneros Group – Characterization of Data Availability
Project phase:		
	Data source	Graneros Group (Skull Creek Shale, Newcastle Sandstone, Mowry Shale, and Belle Fourche Shale)
Geologic Data (Section 1)		
Areal extent	Core data, well logs	
Depth	Core data, well logs	*"Fairly well characterized in the well field; less complete upgradient."*
Thickness	Core data, well logs	
Lithology/ depositional history	Core data and literature about the site	
Petrology/mineralogy	Core data	
Hydrogeologic Data (Section 2)		
Porosity	Core data; literature/historic studies	
Intrinsic permeability (V and H)	Core data; literature/historic studies	
Transmissivity and storativity	Pump tests; literature/earlier studies	
Hydraulic conductivity	Pump test data	
Wells/artificial penetrations	UIC permit application	

Geochemical Data (Section 3)		
Oxidation states and forms of uranium in solids (e.g. uraninite, coffinite, residual U in solids)	Core data; petrographic and mineralogic analyses	
Reactive and non-reactive minerals such as hematite and magnetite, carbonates, clays, sulfides, sulfates, etc.	Core data; petrographic and mineralogic analyses	

		Morrison Formation – Characterization of Data Availability
Project phase:		
	Data source	Morrison Formation
Geologic Data (Section 1)		
Areal extent	Core data, well logs	
Depth	Core data, well logs	*"Fairly well characterized in the well field; less complete upgradient."*
Thickness	Core data, well logs	
Lithology/ depositional history	Core data and literature about the site	
Petrology/mineralogy	Core data	
Hydrogeologic Data (Section 2)		
Porosity	Core data; literature/historic studies	
Intrinsic Permeability (V and H)	Core data; literature/historic studies	
Transmissivity and storativity	Pump tests; literature/earlier studies	
Hydraulic conductivity	Pump test data	
Wells/artificial penetrations	UIC permit application	
Geochemical Data (Section 3)		

Oxidation states and forms of uranium in solids (e.g. uraninite, coffinite, residual U in solids, etc.)	Core data; petrographic and mineralogic analyses	
Reactive and non-reactive minerals such as hematite and magnetite, carbonates, clays, sulfides, sulfates, etc.	Core data; petrographic and mineralogic analyses	*"Cores in Section XXX are upgradient of the ore bodies and have an oxidized mineral assemblage that includes hematite, clays, minor calcite, etc."*